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RESEARCH ARTICLE

Influence of particle grading on the hygromechanical properties of hypercompacted earth

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Abstract

Civil engineering research is increasingly focusing on the development of sustainable and energy-efficient building materials. Among these materials, raw (unfired) earth constitutes a promising option for reducing the environmental impact of buildings over their entire service life from construction to demolition. Raw earth has been used since old times but only recently has acquired prominence in mainstream building practice. This is mainly because of the development of novel methods to enhance the mechanical, hygroscopic and durability properties of compacted earth without increasing carbon and energy footprints. In this context, the present paper studies the dependency of the strength, stiffness, moisture capacity and water durability of compacted earth on particle grading. Results indicate that the particle size distribution is a key variable in defining the hygromechanical characteristics of compacted earth. The effect of the particle size distribution on the hygromechanical properties of compacted earth may be as important as that of dry density or stabilisation. This study suggests that a fine and well-graded earth mix exhibits higher levels of strength, stiffness, moisture capacity and water durability than a coarse and poorly-graded one.

Keywords Raw earth material · Soil suitability · Hypercompaction · Durability

1 Introduction

The construction sector accounts for 30% of the worldwide carbon emissions and consumes more raw materials than any other economic activity on the planet. It is therefore understandable that civil engineering research is currently focusing on the development of resource-effective construction materials that can reduce the environmental impact of buildings during construction, operation and demolition.

Raw (unfired) earth is a particularly attractive construction material that can cut down energy consumption and carbon production over the entire lifetime of buildings, thus resulting in lower levels of embodied, operational and end-of-life energy [1]. Unstabilised raw earth consists in a mix of clay, silt and sand, usually locally sourced, which is blended with water and compacted without further transformation [2]. The amount of energy required for the transportation and manufacturing of raw earth is relatively low compared to conventional construction materials. Similarly, the use of raw earth as a construction material facilitates the disposal or recycling of demolition waste at the end of service life. Raw earth also exhibits a strong ability to store or release ambient moisture while exchanging latent heat with the surrounding environment. This increases the comfort of occupants and reduces the operational energy required for conditioning indoor temperature and humidity [1, 3, 4]. Raw earth is not a novel material as it has been used for the construction of human dwellings since thousands of years. Only recently, however, new fabrication techniques have been proposed to enhance the strength, stiffness and durability of compacted earth to the levels required by modern construction without significantly increasing the carbon and energy footprints. Mechanical properties of raw earth are usually improved by adding chemical stabilisers, such as cement and lime, and/or by densifying the material through compaction or vibration. An innovative "hypercompaction" method has been

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recently proposed by [5] whereby a large compaction effort of 100 MPa is applied to the earth producing a material with a very low porosity of about 13%. As a term of comparison, natural sedimentary rocks exhibit similar levels of porosity.

While material stabilisation has attracted large research interest, the design of the base earth mix and, in particular, the identification of the optimal plasticity and grading characteristics have been rather overlooked. Fine soils retain more water than coarse soils thus resulting in stronger hygroscopic behaviour, which increases inter-particle capillary bonding and moisture buffering capacity. Nevertheless, an excessively large fine fraction may weaken the mechanical behaviour and undermine material durability. This means that not all soils are suitable for earth building or, at least, not all soils are suitable for all types of earth building. A comprehensive study of the optimal index properties of earthen materials was published by Delgado and Guerrero [6], who emphasized the importance of developing technical guidelines to select appropriate earth mixes for each building technique.

The present paper contributes to overcome this gap of knowledge by investigating the influence of particle size distribution on the hygromechanical and durability characteristics of compacted earth. In this study, different earth mixes with distinct particle gradings were hypercompacted at their respective optimum water contents. The stiffness and strength of these different materials were then measured by performing unconfined compression tests while the hygroscopic properties were assessed by measuring the moisture buffering value (MBV). The durability of the material against water erosion was also investigated by means of immersion tests.

Measurements indicate that particle size distribution and clay content have a marked influence on the mechanical, hygroscopic and durability properties of hypercompacted earth. A fine and well-graded earth mix exhibit better mechanical performance, larger hygroscopic capacity and greater water durability than a coarse and poorly-graded earth mix at similar dry density. The effect of particle grading on material properties appears at least as significant as that of dry density.

The study also identifies one important challenge ahead, which is the development of effective stabilisation techniques that can improve the water durability of raw earth without undermining the advantageous environmental characteristics of the material.

2 Materials and methods

2.1 Base soil and index properties

This study made use of a base soil provided by the Bouisset brickwork factory from the region of Toulouse (France). The plasticity properties of the base soil were measured on the fine fraction, i.e. the fraction smaller than 0.400 mm, according to the norm AFNOR [7]. These measurements suggest that the material is a low plasticity clay, which complies with the requirements for the manufacture of compressed earth bricks according to the recommendations by Houben and Guillaud [8] and AFNOR [9]; CRATerre-EAG [10].

The particle size distribution of the base soil was instead determined by means of wet sieving and sedimentation in compliance with the norms AFNOR [11] and AFNOR [12] while the specific gravity of the solid particles was measured by means of pycnometer tests according to the norm AFNOR [13]. Figure 1 shows the particle size distribution of the base soil together with the recommended limits suggested by MOPT [14] and AFNOR [9]; CRATerre-EAG [10] for the manufacture compressed earth bricks. Inspection of Fig. 1 indicates that the base soil can be classified as a well-graded silty clay, which lies close to the upper limit of current recommendations. All index properties of the base soil are summarized in Table 1.

Previous mineralogical studies of the base soil [15] have also indicated a predominantly kaolinitic clay fraction, which is suitable for earth construction because of the low specific surface (10 m^2/g) and the consequently small swelling/shrinkage potential upon wetting/drying. The same studies [15] have also characterized the hygromechanical properties of the material highlighting a reasonably good durability against water erosion.

The base soil was blended with variable proportions of a silica sand to obtain three distinct earth mixes with different clay fractions (i.e. with different fractions exhibiting particle sizes smaller than 0.002 mm). Figure 2 shows the particle size distribution of the added silica sand, whose grading is monodisperse with almost all particles having a size comprised between 0.06 and 2 mm.

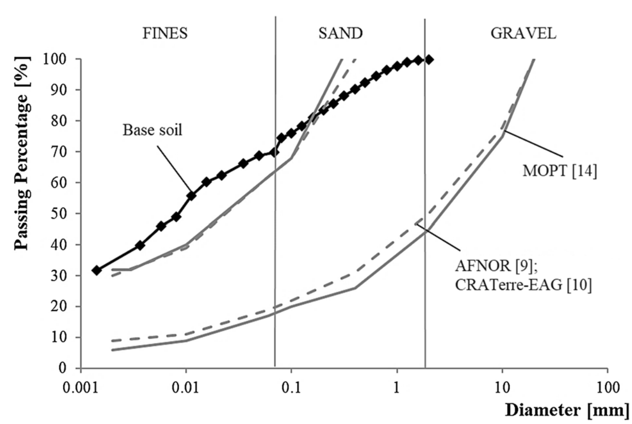

Fig. 1 Particle size distribution of the base soil in relation to existing recommendations for the manufacture of compressed earth bricks by MOPT [14] and AFNOR [9]; CRATerre-EAG [10]

Table 1 Index properties of the base soil

Grain size distribution	
Gravel content (> 2 mm, %)	0
Sand content (≤ 2 mm, %)	31
Silt content (≤ 63 µm, %)	35
Clay content (≤ 2 µm, %)	34
Specific gravity	2.65
Atterberg limits	
Plastic limit (%)	18.7
Liquid limit (%)	29.0
Plasticity index (%)	10.3

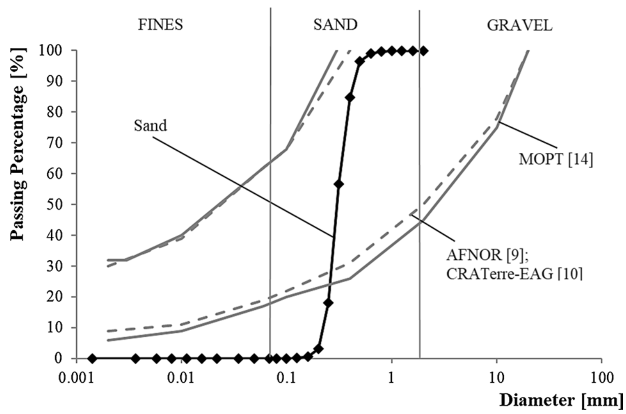

Fig. 2 Particle size distribution of silica sand in relation to existing recommendations for the manufacture of compressed earth bricks by MOPT [14] and AFNOR [9]; CRATerre-EAG [10]

Earth mix 1 does not contain any added sand and there-

Table 2 Base soil and added sand percentages for the different earth mixes

Material	Base soil percentage [%]	Added sand percentage [%]
Earth mix 1 (base soil)	100	0
Earth mix 2	66	34
Earth mix 3	32	68

fore coincides with the base soil while earth mixes 2 and 3 contain increasing percentages of added sand. Table 2 shows, for each earth mix, the respective percentages of base soil and added sand while Table 3 summarises the resulting composition of the three earth mixes in terms of sand, silt and clay contents.

Figure 3 shows the particle size distributions of the three earth mixes together with the recommended bands suggested by MOPT [14] and AFNOR [9]; CRATerre-EAG [10] for

Table 3 Physical composition of the different earth mixes

Material	Sand [%]	Silt [%]	Clay [%]
Earth mix 1 (base soil)	≈ 31	≈ 35	≈ 34
Earth mix 2	≈ 54	≈ 23	≈ 22
Earth mix 3	≈ 78	≈ 11	≈ 11

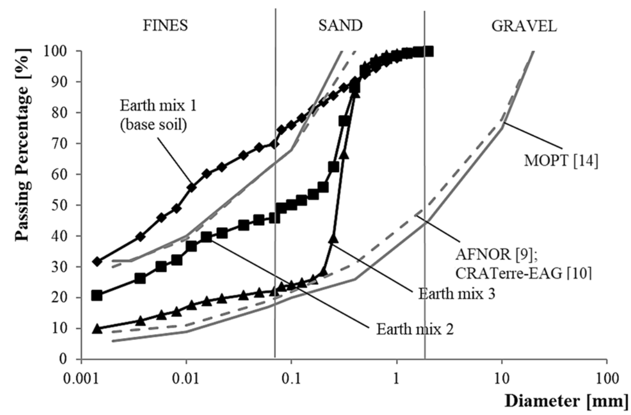

Fig. 3 Particle size distribution of earth mixes in relation to existing recommendations for the manufacture of compressed earth bricks by MOPT [14] and AFNOR [9]; CRATerre-EAG [10]

compressed earth bricks. Inspection of Fig. 3 indicates that the three earth mixes span the entire recommended range of clay content, which is the fraction smaller than 0.002 mm. Earth mix 1 is well-graded while earth mixes 2 and 3 exhibit a bimodal (gap-graded) particle size distribution. This is particularly true for earth mix 3, whose particle size distribution cuts across the entire recommended band from the upper to the lower limit. Nevertheless, in spite of these significant differences in grading, all earth mixes fall inside or close to the recommended band and are therefore compatible with existing guidelines.

2.2 Hypercompaction of earth samples

Compaction is an engineering technique to densify earth by packing particles close together and, hence, reducing the pore volume. In this work, each earth mix was compacted by applying a very high static pressure of 100 MPa to produce extremely dense samples with porosities as low as 13%. This heavy compaction technique was originally proposed by [5, 16], under the name of "hypercompaction", to produce unstabilised earth bricks with levels of stiffness and strength similar to those of conventional building materials. For example, the hypercompacted unstabilised earth bricks tested by Bruno et al. [17] exhibited values of compressive strength comparable to those of cement-stabilised and fired earth bricks [18, 19] (Table 4).

Table 4 Compressive strength of unstabilised, stabilised and fired earth bricks

Material	Compressive strength [MPa]
Hypercompacted unstabilised earth bricks (Bruno et al. [16])	14.6
Compacted stabilised earth bricks (Guetlala and Guenfoud [18])	From 5.2 to 12.9
Standard fired earth bricks (ASTM C270 [19])	From 6.9 to 27.6

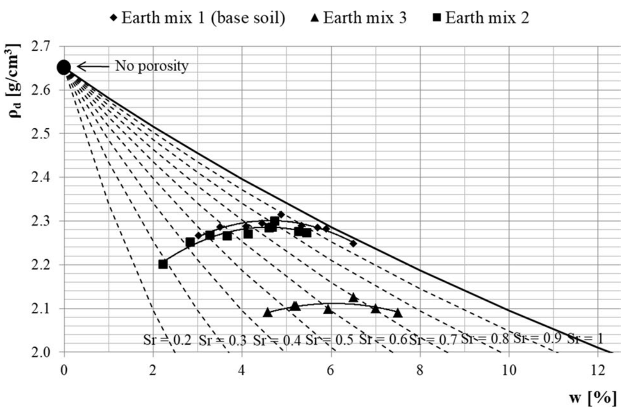

Fig. 4 Hypercompaction curves of the three earth mixes subjected to a static pressure of 100 MPa

Table 5 Optimum water contents and corresponding maximum dry densities for the three hypercompacted earth mixes

Material	Optimum water content [%]	Maximum dry density [g/cm³]
Earth mix 1 (base soil)	4.9	2.31
Earth mix 2	4.7	2.30
Earth mix 3	6.5	2.12

In this work, the dry soil was initially mixed with the chosen amount of water and subsequently placed inside three plastic bags to prevent evaporation. The moist material was left to equalize for at least 1 day so that moisture could redistribute, before being placed inside a stiff cylindrical steel mould with a diameter of 50 mm where it was vertically compacted under a pressure of 100 MPa by using a load-controlled press. Pressure was applied by two cylindrical aluminium pistons acting on the top and bottom extremities of the sample. This double-piston compression reduces the effect of friction between the inner mould surface and the sample sides, thus increasing stress uniformity inside the material. Eight fine longitudinal grooves were cut on the surfaces of the pistons to facilitate drainage of pore air, and possibly pore water, during compaction. Additional details about the hypercompaction procedure are available in Bruno et al. [17].

Figure 4 presents the values of dry density, ρ_d measured after hypercompaction of each earth mix at different water contents, w. Figure 4 also shows the equisaturation lines, which converge towards the theoretical ''no porosity'' point defined by a zero water content and a dry density equal to the density of the solid particles. Inspection of Fig. 4 indicates that the finer and better-graded earth mixes 1 and 2 exhibit almost identical compaction curves with higher dry densities than the coarser and poorer-graded earth mix 3. Earth mixes 1 and 2 present an almost identical value of the optimum water content (i.e. the water content corresponding to the highest dry density), which is comprised between 4.7 and 4.9%. This value is markedly lower than the optimum water content of earth mix 3, which is about 6.5%. Table 5 summarizes the optimum water contents and the corresponding values of the maximum dry densities for the three hypercompacted earth mixes.

3 Results

A range of hygromechanical tests was performed to determine the strength, stiffness, moisture buffering capacity and water durability of the three hypercompacted earth mixes. All tests were performed on cylindrical samples that were hypercompacted under a static pressure of 100 MPa at their respective optimum water contents (see Table 5). The cylindrical samples had a diameter of 50 mm while the height was either 100 mm or 50 mm depending on the type of test as explained later. Cylindrical samples were preferred to bricks to avoid sharp corners that could induce stress concentration during fabrication and testing.

3.1 Unconfined compression tests

Unconfined compression tests were conducted on cylindrical hypercompacted samples with a diameter of 50 mm and a height of 100 mm. An aspect ratio of two was chosen to limit the spurious radial confinement caused by the friction between the sample extremities and the press plates during axial compression. Before testing, all samples were equalized inside a climatic chamber at a temperature of 25 °C and a relative humidity of 62%. This was considered necessary to avoid the influence of potentially different ambient conditions on the measured values of strength and stiffness. During the equalization phase, the samples were weighted every day until their mass changed less than 0.1% over a period of at least 1 week, which generally took about 15 days.

A first series of tests was performed to measure the strength of the three hypercompacted earth mixes. During these tests, the samples were compressed under a constant axial displacement rate of 0.001 mm/s, which allowed recording also the post-peak part of the stress-strain curve. The displacement rate was the slowest that could be applied by the press and was chosen to obtain a regular stress-strain curve without instabilities [17]. Two samples were tested for each earth mix to confirm the repeatability of measurements and to reduce errors. The final peak strength was then calculated as the average of these two measurements.

Figure 5 shows the peak values of compressive strength for each earth mix together with the corresponding values of dry density (measured in g/cm^3) in brackets. Inspection of Fig. 5 indicates that, as expected, compressive strength increases with growing density, though this increase is far from linear due to the influence of the earth grading on the material response.

A second series of unconfined compression tests was performed to compare the stiffness of the three hypercompacted earth mixes. The Young's modulus was measured by performing five axial loading-unloading cycles, with a constant loading rate of 0.005 MPa/s, between one-ninth and one-third of the peak strength as measured from previous tests. The axial strain was measured between two points located at a distance of 50 mm by means of extensometers mounted symmetrically with respect to the middle of the sample. The axial strain was the average of two measurements taken by two distinct extensometers (Model 3542-050 M-005-HT1—Epsilon Technology Corp.) placed on diametrically opposite sides of the sample.

Based on the assumption that material behaviour is elasto-plastic during loading but essentially elastic during unloading, the Young's modulus was determined from the unloading branches of the five cycles. In particular, the Young's modulus was calculated as the average slope of the five unloading branches in the stress-strain plane. Figure 6 shows the measured values of Young's modulus for the three different earth mixes, together with the respective values of dry density (measured in g/cm^3) in brackets. Similarly to compressive strength, the Young's modulus increases with growing dry density but this increase is strongly not linear due to the influence of the earth grading.

Inspection of Figs. 5 and 6 indicates that significant differences of stiffness and strength exist between earth mixes 1 and 2 despite an almost identical value of dry density. An explanation of this result might be found in the different physical composition of the two mixes. Earth mix 2 is a blend of silty clay and sand with a bimodal (gap-graded) particle size distribution while earth mix 1 is a well-graded silty clay (Fig. 3). This indicates that dry density cannot be considered as the only factor governing the mechanical behaviour of hypercompacted earth but particle grading also plays an important role.

3.2 Moisture buffering value (MBV) tests

The capacity of the hypercompacted earth to adsorb and release ambient humidity was experimentally assessed through the measurement of the moisture buffering value (MBV). The MBV "indicates the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air" [20].

Hypercompacted cylindrical samples with 50 mm diameter and 100 mm height were exposed to step cycles of relative humidity, between 75% and 53%, at a constant temperature of 23 °C inside a climatic chamber (CLIMATS Type EX2221HA). Each humidity level was maintained for 12 h

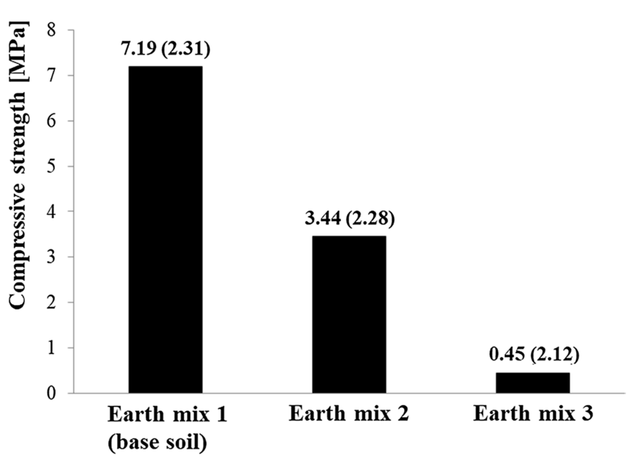

Fig. 5 Compressive strength: results of unconfined compression tests. Values in parenthesis indicate dry density in g/cm^3

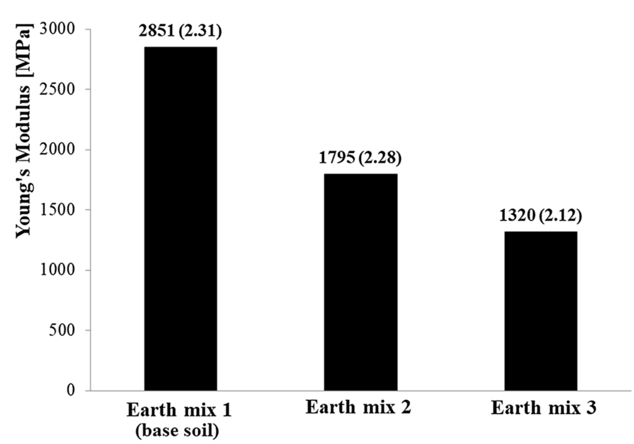

Fig. 6 Young's modulus: results of unconfined loading-unloading cycles. Values in parenthesis indicate dry density in g/cm^3

while the sample mass was recorded every 2 h. This experimental procedure is consistent with the norm ISO 24353 [21] for the characterization of the hygrothermal behaviour of building materials exposed to cyclic variations of relative humidity over a daily (24 h) period of time.

Each cylindrical sample was placed upright inside an aluminium foil pan so that only the top and lateral surfaces were directly exposed to the atmosphere inside the climatic chamber. The total area of the exposed surface was therefore about 0.018 m^2, which is higher than the minimum value of 0.010 m^2 required by the norm ISO 24353 [21]. Three samples were tested for each earth mix to confirm the repeatability of measurements and to reduce errors, with the final MBV calculated as the average of the three measurements.

Before the test, all samples were equalized at a temperature of 23 °C and a relative humidity of 53%. Equalization was assumed complete when the mass of the sample changed less than 0.1% over a period of at least 1 week (this took generally 2 weeks). After equalization, the samples were exposed to cyclic changes of relative humidity as previously described and two different MBVs were calculated, corresponding to the uptake and release stages of each cycle, according to the following equation:

$$\mathrm{MBV} = \frac{\Delta m}{S\Delta\%RH} \quad (1)$$

where Δm is the absolute value of the sample mass variation (in grams), S is the exposed surface (in square meters) and $\Delta\%RH$ is the imposed relative humidity change (in percentage). The value of Δm measured at the end of the high humidity stage provides the "MBV uptake" while the value of Δm measured at the end of the low humidity stage provides the "MBV release". To take into account the small change of sample dimensions caused by the swelling/shrinkage of the earth, the exposed surface was calculated as the average of three height measurements and three diameter measurements taken both at the beginning and end of each humidity stage.

Figure 7 shows that the MBV is larger during moisture uptake than during moisture release but this difference reduces as the number of cycles increases and the material converges towards steady state. Steady state is conventionally defined as the occurrence of three consecutive "stable" cycles where moisture uptake at a humidity of 75% is approximately equal to moisture release at a humidity of 53%. In general, five cycles were sufficient to achieve steady state.

The final MBV of the material is conventionally measured under steady state conditions and it is calculated as the average of the uptake and release values of the last three stable cycles. The final MBVs of the three hypercompacted earth mixes measured the present work are summarized in Table 6, which shows that earth mix 1 exhibits a higher

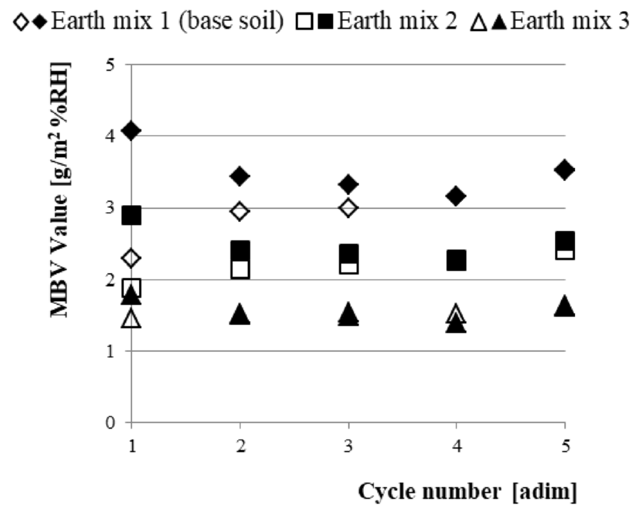

Fig. 7 MBVs measured during moisture uptake and release stages of humidity cycles. Solid markers indicate MBV uptake while hollow markers indicate MBV release

Table 6 MBVs under steady state conditions

Sample ID	MBV [g/ m^2 %RH]
Earth mix 1 (base soil)	3.3
Earth mix 2	2.3
Earth mix 3	1.5

moisture buffering capacity than the other two mixes. This is due to the larger fine fraction, and hence the greater water retention capacity, of earth mix 1 compared to the other two mixes. In particular, the MBV increases almost linearly with growing clay content (see Tables 3 and 6) being twice as large for earth mix 1 as for earth mix 3. Similar experimental observations were made for different materials by Jaquin et al. [22] and Beckett and Augarde [23].

Results from MBV tests are often presented in the form of moisture adsorption curves, which record the hygroscopic behaviour of the material throughout the cyclic variation of relative humidity. The moisture adsorption is defined, at any given time, as the ratio between the variation of sample mass during a cycle (i.e. the difference between the current and initial mass of the sample) and the area of the exposed surface. Figure 8 shows the moisture adsorption curves recorded for each earth mix during the last stable cycle when the hygroscopic behaviour is virtually reversible with the moisture uptake being approximately equal to the moisture release.

Figure 9 presents the MBV of earth mix 1 measured during the present work together with the MBV measured by Bruno et al. [17] on a different hypercompacted earth mix

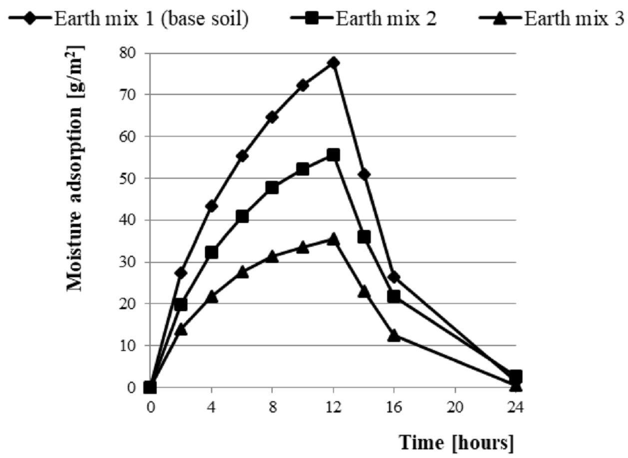

Fig. 8 Moisture adsorption curves during the last stable cycle of each earth mix

and the MBVs measured by Rode et al. [20] on a variety of standard building materials. Note that the MBV reported by Bruno et al. [17] was measured on earth bricks that were hypercompacted according to a similar manufacturing procedure to that adopted in the present work. Inspection of Fig. 9 indicates that earth mix 1 exhibits an excellent hygroscopic performance with a MBV which is slightly less than that measured by Bruno et al. [17] but about seven times higher than that of traditional building materials, such as fired clay or concrete bricks, as reported by Rode et al. [20].

3.3 Water durability tests

Durability against water erosion was investigated by means of immersion tests on cylindrical hypercompacted samples of 50 mm diameter and 50 mm height according to the standard experimental protocol described in [13]. Before testing, all samples were equalized at the laboratory atmosphere, i.e. at a temperature of 25 °C and a relative humidity of 40% ± 5%, until the mass changed less than 0.1% over a period of at least 1 week (this took generally 3 weeks). After equalization, the sample was weighted to record its initial mass m_i and subsequently submerged in water for 10 min. The sample was then removed from water and equalized again to the laboratory atmosphere to attain the same moisture content as before immersion. After equalization, the final sample mass m_f was recorded and introduced, together with the initial mass m_i, in the following equation to calculate the percentage mass loss $\%\Delta m$ experienced by the sample during immersion:

$$\%\Delta m = \frac{m_i - m_f}{m_i} \times 100 \tag{2}$$

Table 7 summarizes the results from all tests, which confirms that the hydrophilic nature of the earth has a negative impact on the water durability of the hypercompacted samples. All samples showed marked mass losses and exhibited numerous cracks after immersion. Nevertheless, the finer and better-graded earth mix 1 experienced a relatively small mass loss of only 13% compared to 30% for earth mix 2 and a complete sample dissolution for earth

Fig. 9 MBV of earth mix 1 compared to the MBVs of other building materials as reported by Bruno et al. [16] and Rode et al. [20]

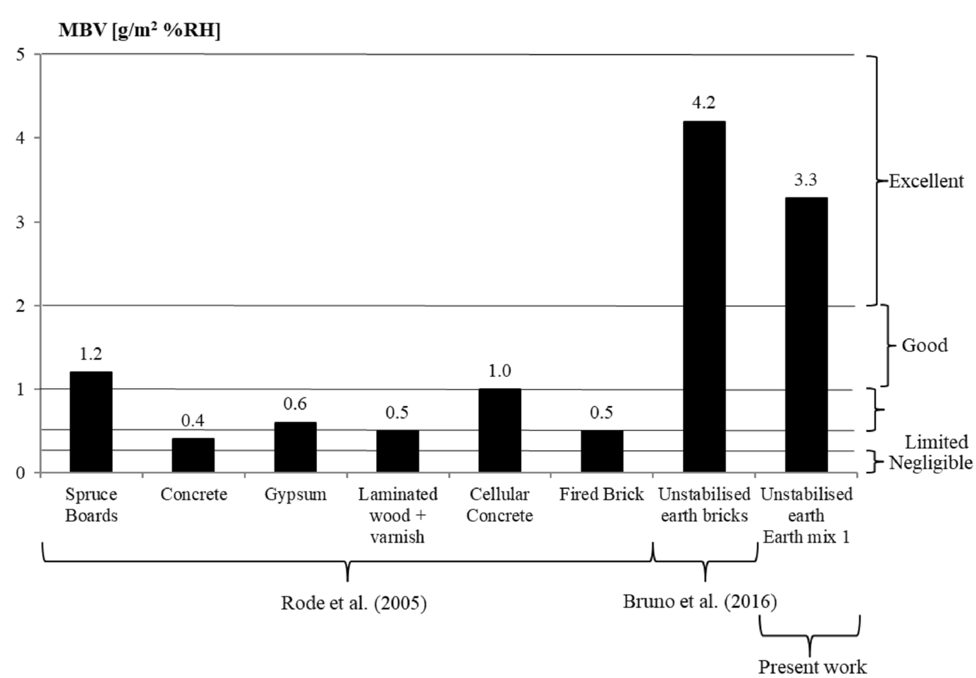

Table 7 Percentage mass loss during immersion tests

Sample ID	%Δm [%]
Earth mix 1 (base soil)	≈ 13
Earth mix 2	≈ 30
Earth mix 3	Complete dissolution after 4′30″

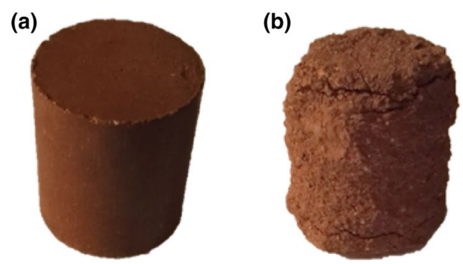

Fig. 10 Hypercompacted earth mix 1 before (**a**) and after (**b**) immersion in water

mix 3. Once again, these disparities might be attributed to the different dry densities of the tested samples but also to the distinct particle size distributions of the three mixes.

Figure 10 shows two pictures of the sample of earth mix 1 taken before (a) and after (b) immersion in water. These pictures indicate that immersion in water produces a significant erosion of the sample surface even for the relatively durable earth mix 1. This deterioration is expected to negatively affect also the strength and stiffness of the material, though this particular aspect has not been evaluated in the present work but will form part of future research.

4 Conclusions

The utilization of raw (unfired) earth as a building material is attracting the interest of engineers and architects worldwide due to environmental and economic advantages but also to the availability of novel fabrication techniques that can meet the demands of modern construction.

Past research has indicated that densification of unstabilised earth by means of heavy compaction may improve strength and stiffness to levels that are comparable to those of traditional materials such as fired bricks, concrete blocks and stabilised earth. This paper has shown that dry density is not, however, the only important factor governing the engineering properties of unstabilised earth but particle size distribution has also a significant influence on stiffness, strength, hygrothermal inertia and water durability. This conclusion is supported by a wide experimental campaign that has been performed during the present work on three distinct earth mixes characterised by significantly different particle size distributions but compacted under the same pressure. This testing campaign included unconfined compression tests, moisture buffering tests and immersion tests. Results suggest that the use of a fine and well-graded earth mix can significantly improve the strength, stiffness, moisture capacity and water durability of the material compared to a coarse and poorly-graded earth mix compacted at a similar density. Importantly, the enhancement of water durability, albeit insufficient for mainstream building, may reduce the extent of chemical stabilisation that is required to comply with current regulations.

All three earth mixes tested in the present work are compatible with particle grading recommendations that have been published in the literature and may therefore be deemed suitable for construction. Nevertheless, the three mixes exhibited markedly different behaviour during tests, which raises questions about the validity of current recommendations and suggests the necessity of considering additional grading features such as, for example, the regularity of particle size distribution.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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